Flow regime changes in three catchments with different landforms following ecological restoration in the Chinese Loess Plateau

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Abstract: The Chinese Loess Plateau is known as one of the most severe soil erosion regions in the world. Two ecological restoration projects, i.e., the integrated soil conservation project since the 1970s and the "Grain for Green" project since 1999, have been progressively implemented to control the soil erosion in this area. Ecological restoration has greatly changed flow regime over the past five decades. However, the mechanism of how flow regime responds to ecological restoration among landforms remains poorly understood. In this study, we investigated the temporal dynamics of flow regime in three catchments, i.e., Wuqi, Honghe and Huangling hydrological stations, respectively representing the loess hilly-gully, loess table-gully and rocky mountain (covered by secondary forest) areas in the Chinese Loess Plateau, using daily hydrological data during the 1960s–2010s. The nonparametric Mann-Kendall test, Pettitt's test and daily flow series were used to investigate the changes of flow regime. Significantly negative trends of annual streamflow were detected at the Wuqi and Honghe stations, except for the Huangling station. The annual baseflow at the Wuqi station showed a significantly positive trend whereas a significantly negative trend was observed at the Honghe station, and there was no significant trend at the Huangling station. It was interesting that baseflow index significantly increased during the whole period in all catchments. However, the trends and change points of daily flow series derived by different percentages of exceedance and extreme series in different consecutive days varied among individuals. Based on the change points analysis of annual streamflow, we divided data series into three periods, i.e., the baseline period (from 1959 and 1963 to 1979, PI), the integrated soil conservation period (1980–1999, PII) and the "Grain for Green" period (2000–2011, PIII). We found that streamflow decreased due to the reduction of high streamflow (exceeding 5% of time within a year) and median streamflow (50%) in PII and PIII at the Wuqi and Honghe stations. However, low flow (95%) increased in PII and PIII at the Wuqi station while decreased at the Honghe station. Streamflow change at the Huangling station was more stable, thus potentially resulting in much less soil erosion in the forestry area than in the other areas. The great improvement in ecological environment on the Chinese Loess Plateau revealed the advantages of ecological restoration in reducing flood amount and compensating streamflow at a regional scale.

Keywords: change point; extreme series; hydrological data; soil erosion; streamflow changes

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1 Introduction

The Chinese Loess Plateau (LP), characterized by a fragmented landscape and severe soil erosion and located in the middle reaches of the Yellow River basin, is an important agricultural area. Sediment yields in several drainage basins on the LP ranged from 3×10^4 to 4×10^4 t/(km^2•a) over recent decades (Shi and Shao, 2000). Soil erosion has resulted in the loss of soil nutrients and agricultural land, which is detrimental to local ecological security and social economic development. To ensure ecological security, Chinese government had implemented the integrated soil conservation project since the 1970s to control soil erosion and increase water supply. The project included constructions of terraces and sediment-trapping dams, afforestation and vegetation cover improvement. These engineering measures significantly and immediately increased streamflow, weakened the magnitudes and peaks of high flow and decreased sediment deposition (Xu et al., 2004; Wang et al., 2011). Approximately 1×10^5 sediment-trapping dams were built before the end of the 1980s. However, these engineering measures will slowly lose their effectiveness and eventually be abandoned due to deposition (Ran et al., 2013; Zhang et al., 2017). The "Grain for Green" project initiated by the Chinese government in 1999 has been widely adopted to improve vegetation cover in China. Studies showed that the LP was experiencing a reduction in precipitation with increasing climate warming. The loess landform is the result of the combined action of running water forces and human activities, which affects the runoff process (Zhang et al., 2008; Zhao et al., 2014; Ma et al., 2015; Yuan et al., 2015; Zhang et al., 2017).

Recently, many studies have found that increases in percentage of area treated by ecological restoration have resulted in streamflow reduction in the middle reaches of the Yellow River basin (Zhao et al., 2013; Zhao et al., 2014). However, it is not clear how hydrological regime changed with the implementation of ecological restoration. Although streamflow has significantly decreased on a large scale, the mechanism of how streamflow change in the context of ecological restoration remains in debate (Shi and Shao, 2000; Zhang et al., 2008; Zhao et al., 2010; Gao et al., 2012; Zhang and Wei, 2012; Zhao et al., 2014; Ma et al., 2015; Zhang et al., 2015). In addition, how streamflow responds to ecological restoration among drainage areas with different landforms is still unclear. To evaluate the role of "Grain for Green" project since 1999 in streamflow, we selected three catchments respectively representing loess hilly-gully, table-gully and rocky mountain to investigate the changes of flow regime in the integrated soil conservation period and the "Grain for Green" period.

2 Study area and methods

2.1 Study area

Three catchments, i.e., the upper reaches of the Beiluo River, the Honghe River and the Juhe River, were selected in the Yellow River basin. The Beiluo River (approximately 3408 km^2) is located in the loess hilly-gully region, of which the outlet is the Wuqi gauge station (Fig. 1). The Beiluo River is characterized by high-intensity rainstorms, a fragmented landscape, crisscrossing galleys and steep slopes. This area is one of the main source areas of coarse sediment in the Yellow River basin. To control severe soil erosion, people adopted a series of soil conservation measures in this area since the 1950s. In 1999, in response to the "Grain for Green" project, environmental construction was conducted in this region. As long-lasting ecological constructions went on, this region has formed secondary forest with deciduous broad-leaved trees, shrub and grasslands (Qin et al., 2010). The Juhe River (approximately 2266 km^2, Huangling station) originates from the Ziwuling Mountains with the landforms of loess hilly-gully and rocky mountain. The catchment is covered by natural secondary forest (canopy closure of 80%), and forest structure is basically formed by trees, shrubs and herbs. The Honghe River (approximately 1272 km^2, Honghe station) is located in the loess table-gully region. The topography in this catchment is mainly composed by plateau, ditch slope and valley. The landform in

this area is characterized by flat terrain with a gentle slope, fertile soils, and mainly farmed crops. The ditch slope is the buffer zone that connects the plateau, with a slope between 7° and 30°, most of which is pasture. The valley below the ditch slope has a "V" shape, with a slope of greater than 25°. Soil conservation measures started in the 1950s (Zhang et al., 2010; Gao et al., 2012; Ran et al., 2013; Du et al., 2014; Zhao et al., 2014).

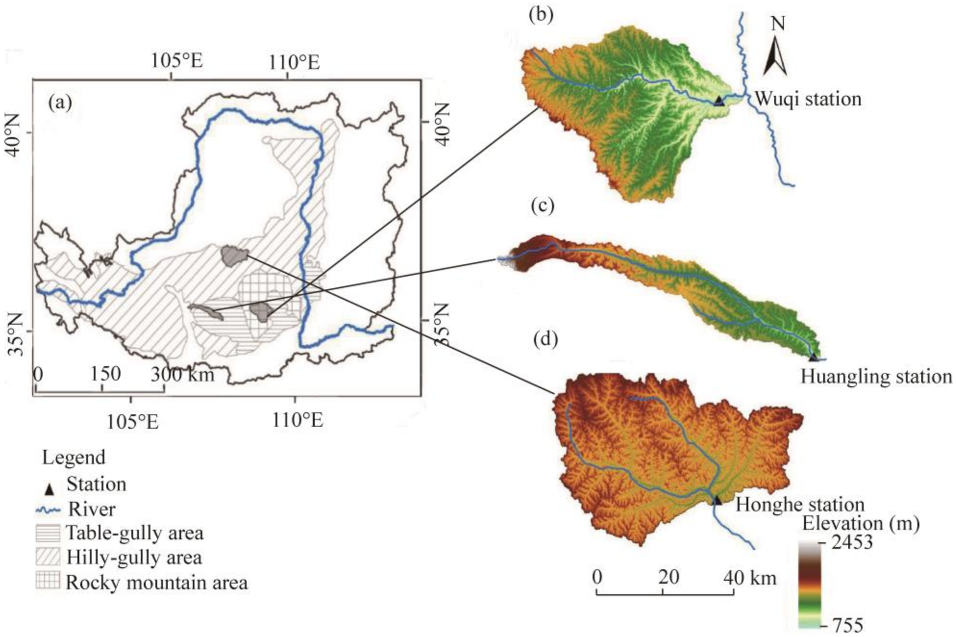

Fig. 1 Study area (a) and locations of the Juhe River (b), upper reaches of the Beiluo River (c) and the Honghe River (d) on the Chinese Loess Plateau. Three gauge stations are shown.

2.2 Data collection

Information of the Beiluo, Juhe and Honghe catchments and three hydrological stations is shown in Table 1. Daily streamflow data at the Wuqi, Huangling and Honghe stations were obtained from the National Earth System Science Data Center (http://www.geodata.cn/). Daily precipitation and potential evapotranspiration (PET) data were collected from the Yellow River Commission Committee and the State Meteorology Bureau of China (http://cdc.nmic.cn/home.do). The precipitation and PET data were interpolated using the Kriging method.

Table 1 Information of the Beiluo, Juhe and Honghe catchments

Catchment	Hydrological station	Latitude	Longitude	Elevation (m)	Number of meteorological station	Area (km^2)	Period
Beiluo (upstream)	Wuqi	109.25°E	35.45°N	1430	8	3408	1963–2011
Juhe	Huangling	108.10°E	35.58°N	1350	10	2266	1967–2011
Honghe	Honghe	107.47°E	36.52°N	2460	8	1336	1959–2011

2.3 Data analysis

2.3.1 Trend analysis

Mann-Kendall (MK) test has been widely used for trend detection in hydrological and climatological time series (Yue et al., 2002). The MK statistic (S) was calculated using the following equations:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_k - x_j), j < k < n, \quad (1)$$

$$\operatorname{sgn}(x_k - x_j) = \begin{cases} 1, x_k - x_j > 0 \\ 0, x_k - x_j = 0 \\ -1, x_k - x_j > 0 \end{cases}, \tag{2}$$

where n is the number of observed data series; and x_j and x_k are the values in periods j and k ($j<k$), respectively.

The MK test has two important parameters in trend detection. These parameters represent significance level, trend direction and change rate. Under the null hypothesis, where there was no trend in the data, the distribution of statistics of S was approximately normally distributed. The variance of S (var(S)) was calculated by:

$$\operatorname{var}(S) = \frac{n(n-1)(2n+5)}{18}. \tag{3}$$

As we derived the variance, the parameter Z (standard test statistic) was used to determine the statistical significance at a level of α. The null hypothesis was rejected if $|Z|>Z_{(1-\alpha/2)}$, where $Z_{(1-\alpha/2)}$ was the value of the standard normal distribution at a probability of exceedance of $\alpha/2$. The Z was calculated as follows:

$$Z = \frac{S}{(\operatorname{var}(S))^{0.5}}. \tag{4}$$

The trend value is estimated using a nonparametric median-based slope method proposed by Sen (Sen, 1965) and extended by Hirsch and Robert (2010):

$$\beta = \operatorname{Median}\left(\frac{x_j - x_k}{j - k}\right), \tag{5}$$

where $1<j<k<n$; and β is the median of all possible combinations of pairs for the whole data series (mm/a).

2.3.2 Change point analysis

The nonparametric Pettitt's test (Pettitt, 1979) was used to calculate the change point in the hydrological and precipitation time series. The Pettitt's statistic ($U_{t,N}$) was calculated using the following equations:

$$U_{t,N} = U_{t-1,N} + \sum_{j=1}^{N} \operatorname{sgn}(x_k - x_j), \tag{6}$$

$$\operatorname{sgn}(x_k - x_j) = \begin{cases} 1, x_k - x_j > 0 \\ 0, x_k - x_j = 0 \\ -1, x_k - x_j > 0 \end{cases}, \tag{7}$$

where N is the number of observed data series.

This test counted an amount of times that a member of the first sample exceeded a member of the second sample. The null hypothesis of Pettitt's test was the absence of a changing point. The test statistic K_N and significance test of dependent probability (p) were calculated as follows:

$$K_N = \operatorname{Max}_{1\le t\le N}|U_{t,N}|, \tag{8}$$

$$p \cong 2\exp(-6(K_N^2)/(N^3+N^2)). \tag{9}$$

3 Results

3.1 Temporal changes in flow and climatic variables

Interdecadal characteristics of streamflow, baseflow, baseflow index (BFI), precipitation and PET are illustrated in Table 2. Streamflow at the Wuqi station was the largest (40.11 mm/a) in the 1960s, declined in the 1970s (27.12 mm/a) and the 1980s (23.71 mm/a), and then slightly increased in the 1990s (33.44 mm/a). However, streamflow drastically decreased at the beginning

of the 21st century (18.21 mm/a). Compared with the 1960s, streamflow decreased by 54.59% in the 21st century. In contrast, baseflow presented a steady increasing trend, as BFI increased from 0.22 to 0.56. Streamflow, baseflow and BFI were stable during the whole period at the Huangling station. Streamflow and baseflow decreased over time at the Honghe station, but the changing rate of BFI was very small. In the context of climate change, precipitation and PET were similarly varied among the three stations.

Table 2 Interdecadal characteristics of flow and climatic variables in the hydrological stations

Hydrological station	Period	Streamflow (mm/a)	Baseflow (mm/a)	BFI (mm/a)	Precipitation (mm/a)	PET (mm/a)
Wuqi	1963–1969	40.11	8.90	0.27	479.36	1731.70
	1970–1979	27.12	9.50	0.35	406.41	1820.55
	1980–1989	23.71	9.79	0.41	402.90	1708.28
	1990–1999	33.44	10.37	0.31	404.66	1843.91
	2000–2011	18.21	11.24	0.56	402.51	1810.62
	1963–2011	27.39	9.83	0.36	415.33	1786.29
Huangling	1967–1969	62.61	39.02	0.62	601.85	1664.24
	1970–1979	44.89	25.55	0.57	553.02	1721.49
	1980–1989	57.87	38.70	0.67	597.58	1530.45
	1990–1999	37.46	27.45	0.73	527.19	1656.08
	2000–2011	50.90	32.51	0.64	565.39	1659.78
	1967–2011	48.91	31.70	0.65	563.66	1643.51
Honghe	1959–1969	50.46	19.96	0.40	553.05	1677.76
	1970–1979	44.03	15.64	0.36	494.37	1763.14
	1980–1989	36.29	14.12	0.39	484.56	1558.43
	1990–1999	27.88	10.38	0.37	485.89	1684.52
	2000–2011	26.64	11.96	0.45	475.98	1666.07
	1959–2011	36.92	14.42	0.39	498.94	1670.22

Note: BFI, baseflow index; PET, potential evapotranspiration.

Trend analyses for annual flow and climate variables are shown in Table 3. At the Wuqi and Honghe stations, significantly decreasing trends in annual streamflow were detected, and the changing rates were –0.32 and –0.45 mm/a, respectively (P<0.001). However, baseflow significantly increased at the Wuqi station (P<0.01), with a rate of 0.04 mm/a, whereas a significantly negative trend was observed at the Honghe station (P<0.001), with a rate of –0.17 mm/a. These results indicated different capacities of ecological restoration to moderate baseflow between Wuqi and Honghe stations. Streamflow and baseflow at the Huangling station showed non-significant trends (P>0.05). The rate of streamflow reduction in the rocky mountain (i.e., Huangling station) was lower than those in the loess hilly-gully and table-gully landforms, indicating that streamflow was stable in the area where vegetation was well preserved. BFI had an upward trend at all stations. In the context of climate change, no significant trend was detected for

Table 3 Trends analysis for annual flow and climatic variables in the hydrological stations

Hydrological station	Streamflow			Baseflow			BFI			Precipitation			PET		
	Z	Sig.	β (mm/a)	Z	Sig.	β (mm/a)	Z	Sig.	β (mm/a)	Z	Sig.	β (mm/a)	Z	Sig.	β (mm/a)
Wuqi	–3.63	0.001	–0.32	3.28	0.01	0.04	4.58	0.001	0.007	–0.99	>0.05	–1.01	–0.96	>0.05	–1.40
Huangling	–1.07	>0.05	–0.27	0.38	>0.05	0.14	2.26	0.01	0.003	–0.82	>0.05	–1.02	–0.65	>0.05	–1.14
Honghe	–3.69	0.001	–0.45	–3.64	0.001	–0.18	2.02	0.01	0.001	–1.59	>0.05	–1.38	–0.80	>0.05	–0.88

Note: BFI, baseflow index; PET, potential evapotranspiration; Z, standard test statistic; Sig., significance; β, median of all possible combinations of pairs for the whole data series.

precipitation and PET in all catchments (P>0.05), although both of them varied with a negative slopes among the three catchments.

To further analyze the changes in streamflow, we investigated the annual variation of daily flow series derived by selecting data at different percentage of exceedance in individual years (Gao et al., 2015; Zhang et al., 2017). Table 4 indicates that, at the Wuqi station, 78.95% of these data records, including streamflow and baseflow records, showed significant trends. In details, 17 of 38 flow series showed significant upward trends, and 12 of 38 flow records showed significant downward trends. At the Huangling station, 89.47% of the flow showed no significant trends, and 10.53% of the flow showed significant upward trends (P<0.01). At the Honghe station, 84.21% of these data records showed significant downward trends (P<0.05). Specially, most of daily streamflow series showed downward trends except the Huangling station. The trend tests of baseflow indicated upward trends at the Wuqi station while downward trends at the Honghe station.

At the Wuqi station, trend tests of daily streamflow records showed that there were significant negative trends in the low-frequency flow (streamflow≥Q70), but significant positive trends in the high-frequency flow (streamflow≤Q80; P<0.05). Both values of low and high baseflow showed significant positive trends (P<0.05) at the Honghe station. The minimum value of streamflow series in 1 d exhibited a significant downward trend and a significant upward trend in consecutive 7 and 30 d, while significant upward trends were detected for baseflow series in consecutive 1, 7 and 30 d. The ratio of Q5 to Q50 for streamflow indicated a significant decreasing trend. However, the ratios of Q95 to Q50 for both streamflow and baseflow showed significant increasing trends.

Table 4 Trend tests for annual variation of daily streamflow and baseflow series constructed using various percentiles for the hydrological stations

Flow record	Wuqi		Huangling		Honghe	
	Streamflow	Baseflow	Streamflow	Baseflow	Streamflow	Baseflow
Q5	–3.22**	2.49*	–0.66NS	–0.79NS	–2.89**	–1.99*
Q10	–2.83**	2.47*	–0.60NS	–0.69NS	–2.28*	–2.49*
Q20	–2.24*	–0.20NS	–0.85NS	–0.26NS	–2.58**	–2.77**
Q30	–2.80**	–0.16NS	–0.65NS	–0.14NS	–2.78**	–3.18**
Q40	–2.67**	0.94NS	–1.11NS	–0.22NS	–2.97**	–3.86***
Q50	–2.76**	1.70NS	–0.52NS	–0.08NS	–3.11**	–4.13***
Q60	–2.77**	1.95NS	0.06NS	0.91NS	–3.01**	–4.73***
Q70	–1.16NS	2.35*	0.75NS	1.16NS	–3.80***	–5.10***
Q80	0.05NS	3.04**	0.78NS	1.62NS	–4.50***	–5.45***
Q90	2.40*	4.34***	0.80NS	1.57NS	–4.90***	–4.96***
Q95	3.92***	4.75***	1.01NS	1.83NS	–4.93***	–4.66***
Min1	–3.63***	5.05***	2.45*	1.80NS	–3.42***	–3.78***
Min7	4.42***	4.85***	1.31NS	1.66NS	–4.07***	–4.18***
Min30	2.05*	4.40***	0.45NS	2.06*	–3.58***	–4.26***
Max1	–2.41*	2.07*	–0.81NS	–0.66NS	–3.05**	–2.03*
Max7	–2.73**	2.11*	–0.60NS	–0.48NS	–2.34*	1.60NS
Max30	–3.28**	2.56*	0.18NS	1.81NS	–2.86**	–1.76NS
Q5:Q50	–2.44*	1.41NS	–0.81NS	–1.54NS	–0.70NS	1.19NS
Q95:Q50	4.83***	2.40**	2.55*	2.91*	–1.96NS	–1.73NS

Note: ***, ** and * indicate significant differences at P<0.001, P<0.01 and P<0.05 levels, respectively, and NS indicates non-significant difference. Q5–Q95 represent the exceedance percentages of streamflow and baseflow. Min1, Min7, and Min30 represent the minimum streamflow and baseflow in consecutive 1, 7 and 30 d, respectively. Max1, Max7 and Max30 represent the maximum streamflow and baseflow in consecutive 1, 7 and 30 d, respectively. Q5:Q50 represents the extreme ratio of high flow. Q95:Q50 represents the extreme ratio of low flow.

At the Huangling station, there was no significant decreasing trend in the low-frequency streamflow and baseflow (≥Q50), and non-significant increasing trends in the high-frequency streamflow and baseflow (≤Q50; P>0.05) was found. For the minimum consecutive records, the minimum streamflow in 1 d and the minimum baseflow in consecutive 30 d statistically increased, while records in the other consecutive days exhibited non-significantly increasing trend. For the maximum consecutive records, the streamflow and baseflow in consecutive 1 and 7 d were no significant change, whereas the streamflow and baseflow in the consecutive 30 d showed a non-significantly increasing trend. There was no significant downward trend for the ratio of Q5 to Q50 series, whereas significant upward trend was detected for the ratio of Q95 to Q50 series.

At the Honghe station, significantly negative trend was identified for all daily series from both streamflow and baseflow. However, the series of Q5:Q50, Q95:Q50 and the maximum baseflow in consecutive 7 and 30 d showed non-significant trends.

3.2 Change points in flow and climatic variables

Pettitt's test was adopted to identify the change point of streamflow before and after ecological restoration. As shown in Figures 2–4, statistically significant change points in annual streamflow, baseflow and BFI were identified.

At the Wuqi station, change points of streamflow occurred in 1979 (P<0.01) and 2002 (P<0.05). Considering the start time of ecological restoration, it took approximately 10 a for streamflow to exhibit a statistically significant change (a relative maximum in the curve) after implementation of the integrated soil conservation project and 3 a following the "Grain for Green" project. However, the change point in 1987 for the baseflow data showed an upward trend. This result indicates that response of baseflow to ecological restoration was slower than that of streamflow. The change points in BFI occurred in 1981 and 2001 with an upward trend. At the Huangling station, no significant change point was detected for annual streamflow and baseflow (P>0.05). However, an upward trend and change point in BFI were identified in 1983 (P<0.01). At the Honghe station, change points in streamflow and baseflow occurred in 1984 with a downward trend (P<0.01), suggesting that the change points occurred approximately 15 years after the initial integrated soil conservation project, while the change caused by afforestation since 1999 has not yet appeared. The change points in BFI happened in 1996 (P<0.01) and 2002 (P<0.05). It should be noted that the speed of flow responding to changes in vegetation cover between the Wuqi and the Honghe stations was different. No change points for annual precipitation and PET were identified in all stations (data not shown).

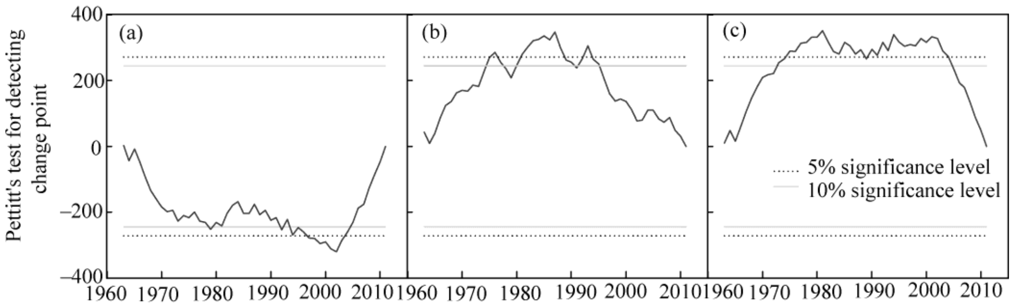

Fig. 2 Pettitt's test for detecting change points in (a) annual streamflow, (b) annual baseflow and (c) baseflow index at the Wuqi station

The results of change point test for all data series are summarized in Table 5. At the Wuqi station, change points were detected in 5 out of 19 streamflow series with significant upward trends, and 12 out of 19 records showed significant downward trends. Change points in the low-frequency streamflow were detected between 1981 and 2002 with a downward trend, but the baseflow in 1993 had an upward trend. This result indicates that the response time of baseflow was slower than that of low-frequency streamflow. For the high-frequency sreamflow, change points occurred between

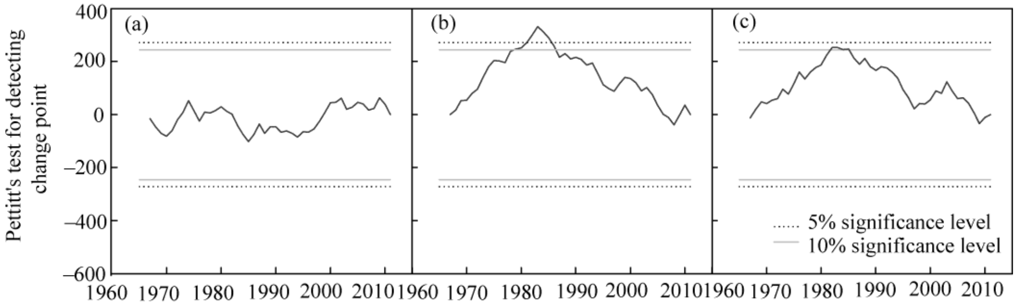

Fig. 3 Pettitt's test for detecting change points in (a) annual streamflow, (b) annual baseflow and (c) baseflow index at the Huangling station

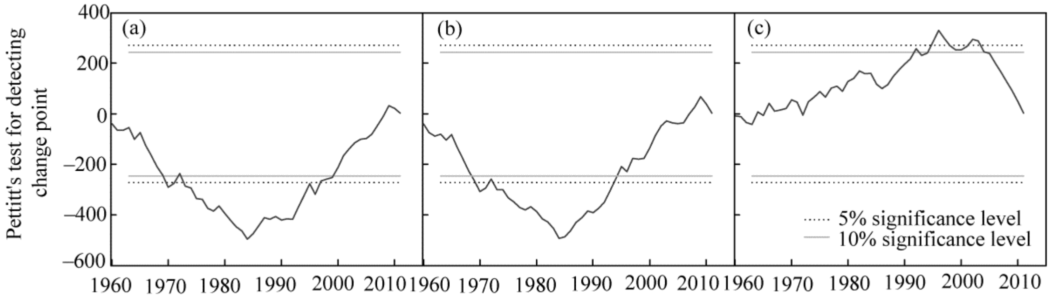

Fig. 4 Pettitt's test for detecting change points in (a) annual streamflow, (b) annual baseflow and (c) baseflow index at the Honghe station

1984 and 2002, but change points of baseflow occurred between 1976 and 1982. The response time of baseflow was shorter than that of high-frequency streamflow. Change points were detected between 1977 and 2002 for the minimum and maximum mean daily flow records in consecutive 1, 7 and 30 d with increasing trends except for the minimum mean daily streamflow in 1 d with decreasing trends, indicating that the response time was almost synchronous between streamflow and baseflow. Two change points in 1979 and 2001 for the maximum mean daily streamflow in consecutive 1, 7 and 30 d showed decreasing trends, whereas one change point in 1993 for the maximum mean daily baseflow showed an increasing trend. The streamflow records of Q5:Q50 showed no change point, and the baseflow had one change point in 1999 with an upward trend. The change points in 1985 and 1999 in the flow records for Q95:Q50 indicated increasing trends.

At the Huangling station, change points were detected in 7 out of 38 records, of which 2 out of 7 records showed significant upward trends in 1983 and 5 out of 7 records showed significant downward trends in 1982. No change point was detected in the exceedance percentage. The minimum mean daily flows in consecutive 1, 7, and 30 d showed change points with downward trends in 1982, except for the minimum mean daily streamflow in consecutive 7 and in 30 d. No change points were detected in the maximum mean daily flows in consecutive 1, 7, and 30 d besides the maximum mean daily flows in consecutive 30 d in 1982 with downward trends. The Q5:Q50 records of streamflow and baseflow indicated no change point, while a change point in 1983 indicated a significant upward trend for the Q95:Q50 records.

At the Honghe station, 94.7% of flow records showed change points between 1983 and 1997 with significant downward trends, and 5.3% showed no change points. In addition, it was noted that the speed of streamflow response to ecological restoration was similar to that of baseflow. The change points in the low-frequency flow were detected in 1984 and 1985, but those in the high-frequency flow were detected in 1985, 1986 and 1990. The minimum mean daily flow records in consecutive 1, 7, and 30 d showed change points in 1990, 1993 and 1994, and 4 change points between 1983 and 1992 were detected for the maximum mean daily flows with downward trends. No change point was detected in the flow records of Q5:Q50, indicating no change point in the high-flow variability. The change points in streamflow record of Q95:Q50 happened in 1997 and

Table 5 Change point detection results for streamflow and baseflow in the hydrological stations

Flow record	Wuqi		Huangling		Honghe	
	Streamflow	Baseflow	Streamflow	Baseflow	Streamflow	Baseflow
Q5	1990*	1993**	-	-	1984**	1984**
Q10	1991*	1993**	-	-	1984**	1984**
Q20	2002*	-	-	-	1984**	1984**
Q30	1981*	-	-	-	1985**	1985**
Q40	1981*, 2002**	-	-	-	1985**	1985**
Q50	1990*, 2002**	1976*	-	-	1985**	1985**
Q60	1998**	1982*	-	-	1985**	1985**
Q70	1998*	1982**	-	-	1985**	1985**
Q80	-	1984**	-	-	1986**	1990**
Q90	1984**	1985**	-	-	1990**	1990**
Q5	1984**	1977**	-	-	1990**	1990**
Min1	1979*, 2002**	1985**	1982**	1982**	1994**	1993**
Min7	1977**, 2002*	1977**, 2002*	-	1982**	1994**	1994**
Min30	1977**	1977**	-	1982**	1990**	1990**
Max1	2001*	1993*	-	-	1992**	1992**
Max7	2001*	1993*	-	-	1992**	1984**
Max30	1979*,2001**	1993**	-	1982**	1983**	1984**
Q5:Q50	-	1999**	-	-	-	-
Q95:Q50	1985**,1999*	1985**,1999*	1983**	1983**	1997**	1994**

Note: ** and * indicate significant differences at P<0.01 and P<0.05 levels, respectively, and "-" indicates non-significant difference.

those in baseflow occurred in 1994 with downward trends, indicating that the response time of ecological restoration on the streamflow lagged behind that on the baseflow in the low-flow variability.

Based on the analysis above, we divided the data in all stations into three periods, i.e., the baseline period from 1959 and 1963 to 1979 (PI), the integrated soil conservation period from 1980 to 1999 (PII) and the "Grain for Green" period from 2000 to 2011 (PIII).

3.3 Hydrological characteristics, precipitation and PET in different periods

To further investigate the changes in flow regime, we calculated mean values and data discrepancy, including extreme ratio (i.e., maximum/minimum ratio), coefficient of variation (CV) and standard deviation (SD) in the pre-change point and post-change point periods of annual streamflow, baseflow, BFI, precipitation and PET in the three periods (Table 6).

At the Wuqi station, compared with PI, annual streamflow decreased by 11.98% in PII and 43.92% in PIII, while annual baseflow and BFI increased by 8.97% and 28.13% in PII and 10.70% and 48.78% in PIII, respectively. Extreme ratio, CV and SD of streamflow and baseflow increased in PII, whereas they decreased in PIII. This result showed that the discretization degrees of streamflow and baseflow in PII were higher than those in PIII. In particular, an increased CV in PII indicates that the reduction in SD is higher than the proportional reduction in the mean value. By contrast, annual precipitation decreased by approximately 9.00% in PI and PII, and PET decreased by 0.44% in PII and increased by 1.49% in PIII. The discretization degrees of annual precipitation and PET in PII were lower than those in PIII. This result indicated that the changes in streamflow and baseflow were not only influenced by climatic factors but also by ecological restoration.

At the Huangling station, changes in extreme ratio, CV and SD were small in PII and PIII. Compared with PI, annual baseflow increased by 15.42% in PII and 13.43% in PIII, and discretization degree of baseflow was higher than those in PII in PIII. Annual precipitation and PET

Table 6 Changes of hydrological characteristics, precipitation, baseflow index (BFI) and potential evaporation (PET) in different periods in the hydrological stations

Index	Hydrological station	PI				PII				PII			
		Mean (mm)	Max/min ratio	CV	SD (mm)	Mean (mm)	Max/min ratio	CV	SD (mm)	Mean (mm)	Max/min ratio	CV	SD (mm)
Streamflow	Wuqi	32.47	3.74	0.39	12.80	28.58	5.78	0.57	16.43	18.21	2.53	0.31	5.70
	Huangling	48.98	5.99	0.62	30.38	47.66	6.28	0.58	27.87	50.90	6.22	0.68	34.78
	Honghe	46.75	5.72	0.43	20.05	28.10	4.96	0.37	10.35	26.64	2.37	0.27	7.29
	Wuqi	9.25	1.60	0.13	1.19	10.08	1.54	0.14	1.37	10.24	1.38	0.09	0.90
Baseflow	Huangling	28.66	3.89	0.47	13.47	33.08	5.56	0.55	18.05	32.51	4.76	0.52	16.87
	Honghe	17.71	3.36	0.32	5.62	10.69	3.18	0.30	3.23	11.96	2.91	0.32	3.86
	Wuqi	0.32	3.83	0.34	0.11	0.41	4.33	0.31	0.13	0.61	2.52	0.29	0.17
BFI	Huangling	0.63	1.76	0.15	0.10	0.71	1.66	0.12	0.09	0.69	2.12	0.19	0.13
	Honghe	0.40	3.19	0.24	0.10	0.39	1.63	0.15	0.06	0.45	1.37	0.09	0.04
	Wuqi	430.10	2.63	0.25	108.73	403.78	2.20	0.21	83.95	402.51	1.69	0.20	81.41
Precipitation	Huangling	564.29	1.79	0.17	98.05	562.39	2.27	0.19	107.06	565.39	1.79	0.18	99.32
	Honghe	523.64	2.34	0.21	111.00	474.48	2.44	0.24	114.14	475.98	2.00	0.22	106.16
	Wuqi	1783.97	1.47	0.08	145.93	1776.10	1.33	0.09	156.67	1810.62	1.24	0.06	104.52
PET	Huangling	1708.28	1.23	0.07	112.04	1593.27	1.49	0.11	180.05	1659.78	1.21	0.05	88.67
	Honghe	1686.22	1.44	0.08	142.64	1644.97	1.38	0.11	173.36	1666.07	1.21	0.06	93.24

Note: PI, the baseline period from 1959 and 1963 to 1979; PII, the integrated soil conservation period from 1980 to 1999; PIII, the "Grain for Green" period from 2000 to 2011; max/min ratio, maximum/minimum ratio; CV, coefficient of variation; SD, standard deviation.

pre- and post-change point showed small changes in different periods, and difference in the data discrepancy was non-significant.

At the Honghe station, extreme ratio, streamflow and baseflow decreased with time. Annual streamflow decreased by 39.88% in PII and 43.01% in PIII. The proportion of baseflow reduction was lower than that of the average streamflow. The changes in annual precipitation and PET were different from those of streamflow and baseflow. Annual precipitation and PET decreased by 9.38% and 2.45% in PII and 9.10% and 1.20% in PIII, respectively. Extreme ratio, CV and SD of precipitation and PET increased in PII but decreased in PIII.

Changes in high (Q5), median (Q50) and low flow (Q95) from individual periods were analyzed to further study the effects of ecological restoration on flow moderation, as shown in Table 7. Relative changes in streamflow and baseflow, defined as the difference between the pre-change point and post-change point dividing by the pre-change point ($(Q_{after}–Q_{before})/Q_{before}$), was calculated in PII and PIII for high (exceeding 5% of time within a year; ΔQ5), median (50%; ΔQ50) and low (95%; ΔQ95) streamflow and baseflow. At the Wuqi and Honghe stations, high streamflow and median streamflow decreased in both PII and PIII, with the proportion ranging from –5.77% to –41.42%. However, relative changes of low streamflow significantly increased in PII and PIII at the Wuqi station but decreased at the Honghe station. Relative changes of high, median and low baseflow increased by 12.84%, 12.92% and 171.00% in PII and by 28.40%, 2.87% and 237.78% in PIII at the Wuqi station, respectively, but they decreased at the Honghe station. In summary, larger relative changes in the flow were observed in PIII at the Wuqi station. At the Huangling station, low and median streamflow and baseflow slightly changed, but high streamflow and baseflow increased by 55.17% and 114.19% in PII and by 36.21 and 81.08% in PIII, respectively.

4 Discussion

4.1 Responses of streamflow and baseflow to ecological restoration

An identified change point for a data series implies that flow regime transformed from one state to another. It should be noted that response of flow regime to ecological restoration between the

Table 7 Relative changes in high (ΔQ5), median (ΔQ50) and low flow (ΔQ95) in PII and PIII

Hydrological station	Flow regime	Relative change (%)					
		PII			PIII		
		ΔQ5	ΔQ50	ΔQ95	ΔQ5	ΔQ50	ΔQ95
Wuqi	Streamflow	–21.46	–5.77	99.00	–41.42	–22.09	118.47
	Baseflow	12.84	12.92	171.00	28.40	2.87	237.78
Huangling	Streamflow	6.25	6.12	55.17	14.02	–6.63	36.21
	Baseflow	6.68	13.82	114.19	23.90	6.58	81.08
Honghe	Streamflow	–29.60	–19.10	–34.38	–22.80	–28.28	–76.40
	Baseflow	–45.31	–38.78	–55.59	–15.12	–33.17	–74.49

Note: PII, the integrated soil conservation period from 1980 to 1999; PIII, the "Grain for Green" period from 2000 to 2011.

Wuqi (loess hilly-gully region) and Honghe stations (loess table-hilly region) was different. The time spent for baseflow response to ecological restoration was longer than that of streamflow at the Wuqi station. The change point of streamflow and baseflow caused by ecological restoration from 1999 may not have appeared yet at the Honghe station. Scott and Smith (1997) reported that response time of catchment was dependent on the extent of vegetation change, the rate of tree growth, the area of ecological restoration, mean annual precipitation, soil permeability property and the other characteristics. Increased infiltration by ecological restoration can recharge to the groundwater system, resulting in a shorter response time. This viewpoint showed that vegetation effects on flow reduction will be efficient only if accumulated vegetation coverage exceeds a critical value approximately 20.00% (Cai, 2001). The percentage of artificial vegetation (afforestation and pasture) area was 4.75% in 1979 but increased to 23.20% in 2002 in the catchment of the Wuqi station. However, artificial vegetation only increased from 5.22% in 1984 to 12.83% in 1999 at the Honghe River. This explains why there was a difference in time spent for both streamflow and baseflow responding to ecological restoration between the two stations.

Furthermore, the reduction in flow varies if the percentage of area treated by revegetation is less than 20.00%. For instance, a large number of sediment-trapping dams, with an area percentage much less than 20.00%, had led to the decrease of streamflow by more than 30.00% in some areas of the Yellow River (Xu et al., 2004; Wang et al., 2011; Moghadam et al., 2015). It was reported that approximately more than 1×10^5 sediment-trapping dams and reservoirs were built in the 1970s in the Chinese Loess Plateau. Obviously, the abrupt change point in streamflow and baseflow related to the construction of engineering measures in the 1970s. Our results showed that response of streamflow and baseflow in different landforms to ecological restoration were different from each other. This result might be due to the gradual change under the impact of soil and water conservation in different catchments. As cumulative area of the conservation measures increased, the characteristics of flow regime were changed. The small-scale implementation of the soil and water conservation measures in PII had an effect on streamflow and baseflow moderation, which was weaker than that in PIII. With the rapid increasing of area treated by ecological restoration, flow regime changes significantly occurred in the 1990s and at the beginning of the 21st century. Although change points also happened in the 1980s, streamflow and baseflow were further regulated in PIII (Table 7). At last, ecological restoration reduced surface runoff generation but increasing infiltration, and water recharge therefore increased baseflow (Zhang et al., 2008; Nie et al., 2011; Nian et al., 2014; Moghadam et al., 2015; Yuan et al., 2015; Zhang et al., 2017).

4.2 Integrated influence of landform/vegetation cover on flow regime

Given that there was no significant trend for precipitation and PET, annual streamflow showed a decreasing trend while annual BFI showed an increasing trend at the Wuqi and Honghe stations. However, the trends of annual baseflow, daily flow with different percentage exceedances and extrema series in different consecutive days were different in the two catchments. The rates of streamflow change mainly depends on human activity intensity, including the percentage of area

treated by soil and water conservation measures and the functional promotion of vegetation community (Wang et al., 2013; Zhao et al., 2014; Zhang et al., 2017). The types of landform also influences streamflow regime to a certain extent, as topography, unsaturated zone and aquifer medium affect rainfall infiltration and water recharge. As shown in Table 2, BFI in the loess table-gully region was larger than that in the loess hilly-gully region before 1969. To our knowledge, in comparison with the deep gully dominated landform in the loess hilly-gully region, the flat loess table is beneficial to rainfall infiltration and thus to formulate a high baseflow depth in a long history.

Besides, in addition to ecological restoration, the hypothesis that difference in landform also gave rise to different scenarios of response of flow to ecological restoration was evidenced in this study. In detail, the cumulative area treated and vegetation cover accounted for 36.4% and 34.2% of the total area at the Wuqi station, and accounted for 38.5% and 42.4% at the Honghe station, respectively (Xu, 1998; Shi et al., 2002; Zhang et al., 2010). The surface coverage changes reduced the conversion of precipitation into streamflow and increased soil water storage, which would change hydrological processes (Zhang et al., 2018). Ecological restoration effectively regulated the daily streamflow, increased streamflow in dry season, and eventually increased baseflow at various frequencies at the Wuqi station. However, such an effect has not yet occurred at the Honghe station. On one hand, this finding may be come from the reason that it needs many years for the water recharge of the increased infiltration because of the thick soil layer (with a thickness of 50–200 m; Wang et al., 2013). On the other hand, it comes from the difference in combination of ecological restoration. Wuqi station is located in the forest steppe and is a typical steppe zone. Apart from reforestation by returning cultivated land, vegetation type of natural vegetation restoration mainly constitutes by shrub grassland. Honghe station is located in the forest zone, and reforestation is the main ecological restoration. Generally, an increased forest cover can promote the hydrological cycle, and there is less streamflow and larger evaporation in the forest catchment than in the grassland catchment (Gao et al., 2012; Zhang and Wei, 2012; Wang et al., 2013; Wan et al., 2014; Zhang et al., 2017). Consequently, high-frequency streamflow and baseflow increased at the Wuqi station but decreased at the Honghe station. Therefore, impacts of ecological restoration and landform comprehensively changed the flow regime in PIII. Due to the expansion of the scale and increased heterogeneity, qualitative judgment and quantitative analysis on the regional scale need further investigation.

Comparison of intra-annual variation between daily streamflow and baseflow, we found that flow regime at the Huangling station (natural secondary forest) is more stable, and soil erosion at the Juhe River is below soil-loss tolerance. Thus it can be assumed that natural secondary forest with a reasonable community functional composition can maintain a more stable hydrological system, which provides an ecological and hydrological theoretical basis for catchment management in the Chinese Loess Plateau. It was reported that a rainstorm occurred on 30 and 31 August 1994 at the Wuqi and Huangling stations (Qin et al., 2010). Although daily precipitation was approximately 82 mm, streamflow was 41 mm at the Wuqi station but only 0.07 at the Huangling station. This phenomenon well explained the assumption above and indicated that natural forest (or reforestation after vegetation succession) could well regulate peak streamflow and recharging flow. Therefore, streamflow must be moderated by more precisely ecological restoration projects in the future, such as involving ecological functional diversity.

5 Conclusions

The response of flow regime to ecological restoration in three catchments respectively representing the loess hilly-gully region, loess table-hilly region and rocky mountain region was investigated in this study. Significantly negative trends in annual streamflow were detected at the Wuqi and Honghe stations but not at the Huangling station. Annual baseflow showed a significantly positive trend at the Wuqi station but a significantly negative trend at the Honghe station. Statistically significant change points in streamflow and baseflow were identified in all stations. Ecological restoration changed flow regime, as the data could be divided into three periods, i.e., the baseline

period from 1959 and 1963 to 1979 (PI), the integrated soil conservation period from 1980 to 1999 (PII) and the "Grain for Green" period from 2000 to 2011 (PIII).

High streamflow and median streamflow decreased in PII and PIII at the Wuqi and Honghe stations. However, low streamflow increased at the Wuqi station but decreased at the Honghe station in PII and PIII. Our finding indicates that ecological restoration can moderate flow by lowering high flow and increasing low flow through water recharge. But such a streamflow moderation effect depends on the scientific and technical aspects of the combination of various ecological restoration measures. In other words, human activities determine the changing direction of streamflow in catchments with various landforms.

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